WATER LINE WITH THE ELECTROSTATIC CONCENTRATOR

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Electrode surface phenomena are known to play a decisive role in forming short-pulse water breakdown [1-3]. Therefore the substantial decrease of field intensity at the electrode surface may lead to the appreciable rise in operational voltage and stored energy of the water forming line, if the average value of the field intensity is maintained. The electrostatic problems are examined in this paper related to the design of a device in which this objective is reached by insertion into water insulation of solid dielectric bodies having relatively small dielectric permittivity (fig.1). The displacement flux rounds the inserts and passes mainly in the gaps between them. The field intensity in the gaps (Region 1) is larger than near the electrodes (Region 2) and is close to that inside the inserts (Region 3). This system may be termed as electrostatic concentrator [4,5] similarly to magnetic flux concentrator [6]. Evaluation of electrostatic concentrator effectiveness may be based on the assumption that the field intensity at the sections mn and $m'n'$ is constant and the displacement flux through the insert is neglected. Then for the middle section of the system having spatial pitch $2d = 2(\delta_1 + \delta_2)$ the approximate equality holds true

$$q' = E_0 \varepsilon_1 d \simeq E_k (\varepsilon_1 \delta_1 + \varepsilon_2 \delta_2), \qquad (1)$$
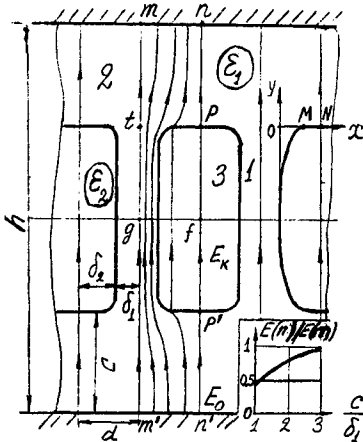

Fig.1. Schematic of the electrostatic concentrator.

where q' is the line charge density, E_k is the field intensity in the gaps and inserts far from electrodes (at the sections pp' and tt', fig.1). The voltage between the electrodes may be expressed

$$U \simeq 2cE_0 + (h - 2c) E_k. \qquad (2)$$

Further, expressing E_0 and E_k by q' from (1) we find the capacitance per unit length of the concentrator section having width $2d$,

$$C' = \frac{q'}{U} = \frac{2\varepsilon_1 d(\varepsilon_1 \delta_1 + \varepsilon_2 \delta_2)}{2c(\varepsilon_1 \delta_1 + \varepsilon_2 \delta_2) + (h - 2c)\varepsilon_1 d}. \qquad (3)$$

Assuming additional condition $h \gg 2c$ we get

$$C' \simeq (2/h)(\varepsilon_1 \delta_1 + \varepsilon_2 \delta_2), \qquad U \simeq hE_k, \qquad (4)$$

$$W' = C'U^2/2 = E_k^2 h (\varepsilon_1 \delta_1 + \varepsilon_2 \delta_2) = E_k W_0'/E_0. \qquad (5)$$

where $W_0' = E_0^2 \varepsilon_1 dh$ is the energy stored in the capacitor without any inserts and field intensity E_0. If $E_k > E_0$ such a storage has E_k/E_0 times larger operational voltage and energy. The capacitance is decreased by the same ratio. If the breakdown conditions near the electrodes in the examined system are defined by the same phenomena as in the system with no inserts then as E_0 the breakdown intensity should be used E_0^+ defined by Martin's formulae [7] or their analogues [8,9] for the anode. The parameter E_k describes the breakdown in the water gaps far from electrodes or the breakdown in the solid inserts where the field

In a properly designed line parameter E_n equal to normal to the interface field component in the water has order of $(\varepsilon_1/\varepsilon_2)E_k$ which is many times less than E_0. This rises expectation that the breakdown formation in the water will be constrained. It may be also guessed that the field intensity in the gaps and the inserts will be limited by the electrical strength of the solid dielectric. The corresponding value E_k may be adopted equal to

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that for the usual breakdown of solid insulation in a quasi-uniform field. This value in the microsecond range is 2÷2.5 times higher than E_0 for dielectrics used as insulators of water lines. For the system shown in fig.1 this estimate is pessimistic because the solid insulation is separated from the electrodes by the water layers.

The experimental data are not avaible in present for the water breakdown in the case when the field intensity at the electrodes is largely reduced compared to its average value. The estimates of E_0 and E_k should be checked experimentally with the very careful choice of the characteristic parameters δ_1/d and δ_2/d and for different form of inserts.

For a given ratio δ_1/d the value c/d should be assumed in such a way that the field intensities at the characteristic points m and n were close. The example of the dependence $E(n)/E(m)$ for the ratio $\delta/d = 1/3$ is plotted in fig.1. The calculation for the rectangular inserts and $\varepsilon_0/\varepsilon_1 = 0$ shows that even for $c/d = 3$ $E(n)/E(m)$ is close to unity.

Real form of the inserts should prevent the field rise at the edges and keep low the normal field component at the interface. An initial choice of the insert form was based on the model for which the ratio $\varepsilon_2/\varepsilon_1$ equals zero. In this case the profile is chosen in such a way that the field intensity at the

boundary is constant up to the point M and then decreases monotonously [10]. In the coordinate system shown in fig.1 this profile is defined by the equations

$$x = \frac{\delta_1}{\pi}\left[2\sqrt{1-\lambda} - \ln\frac{1 + \sqrt{1-\lambda}}{1 - \sqrt{1-\lambda}}\right]; \quad (6)$$

$$y = \frac{2\delta_1}{\pi}\sqrt{\lambda} \qquad (7)$$

where $0 < \lambda < 1$. This profile minimizes the tangent field intensity component at the boundary.

The computer calculations have shown, however, that this profile with the flat section MN is not optimal, if the ratio $\varepsilon_2/\varepsilon_1$ is non-zero. In this case the value of normal field component at the interface becomes significant. The lower value of E_n can be obtained if a profile is formed by a circular arc and an inclined section MN' (fig.2). In this system the tangent field component decreases monotonously and the normal one does not exceed $0.028E_k$ in the water and $1.12E_k$ in the dielectric. The further profile optimization is possible but it gives no confidence that this will result in an additional appreciable decrease of E_n in the concentrator with flat electrodes having inserts separated from the electrodes.

Another performance of an electrostatic concentrator is shown in fif.3. This system is convenient for studies of singlechannel devices with two-dimensional or axisymmetric field. The solid dielectric here contacts the electrodes. The field in the solid dielectric far away from the channel is close to uniform. The boundary field intensity varies from the value E_k close to average (far from the electrodes) to the value approximately equal to $E_0 \simeq$ $\simeq (\mathcal{S}_1/\mathcal{S}_2)E_k$ (at the electrodes). Here $\mathcal{S}_{1,2}$ are the channell sections far away from the electrode and near it, respectively.

The insulator breakdown experiments have shown that in the strictly uniform field having $E_n = 0$ equal to zero the electric strength is practically unaffected by the insulator if it is not hygroscopic [8,9]. Curving the boundary results in a decrease of the breakdown voltage. It is suggested in [9] that this is caused by a normal field component at
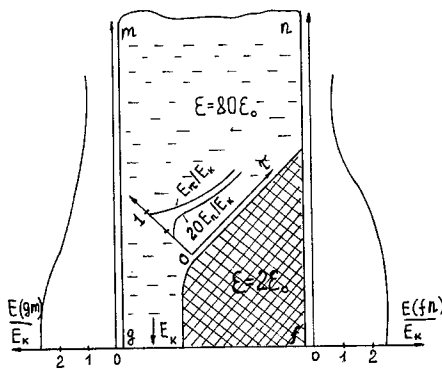

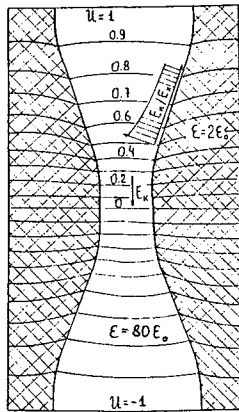Fig.2. Fragment of the concentrator with inclined boundary section MN'

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Fig.3. Concentrator with solid dielectric contacting the electrodes.

the boundary. Therefore this type of the concentrator also requires minimization of E_n along with providing of a smooth fall of E_τ. In this work we performed a small set of experiments which were intended to demonstrate the role of the normal field component. This was achieved by oscilloscopic studies of the breakdown in a cylindric channel with the uniform field and in the channel having the field reduced at the electrode surface (fig.4a,b). Water with the time constant $\tau = \rho \varepsilon_1 \simeq 10^{-7}$ s was used in the experiments. In the first set of experiments larger voltage rise times were used and in the second one theese values were smaller than τ. During the first set (fig.4) the field distribution was defined by water conductivity and the normal intensity component at the boundary was close to zero as the current lines rounded the insert. The breakdown in this set came later than in the channel with smooth walls. In the second set (fig.4), the field was close to an electrostatic one, and according to computer calculation its value reached $E_n = 0.02E_k$. In this set the
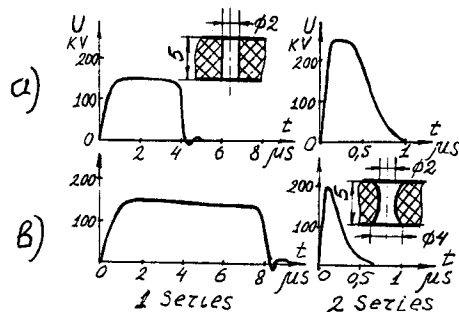
system with smooth walls proved to have greater electric strength and its breakdown occured later. Thus the minimization of the normal field component by variation of the boundary form requires very careful consideration. The example of smooth transition from the narrow channel to the wide section is shown in fig.3. Here the maximum value $E_n = 0.012K_k$ is obtained. Further decrease of the normal field is possible only if the transition section is lengthened.

The drastic way of bringing normal field to zero is the use of non-plane electrodes. In the experiments [8] the increase of electric strength of water line insulators was established if the electrode was convex at the point of contact with the insulator. The example where the condition $E_n=0$ is strictly fulfilled, is shown in fig.5. The boundary is formed here by a field line in the region $abcd$, and one of the equipotential lines is taken as the electrode surface. In this system the maximum field intensity at the electrode section contacting water is $E = 0.5E_k$, the field intensity at the interface reaches maximum value $1.5E_k$ at point b. As in the previously examined cases the field is decreased here near the electrodes and is somewhat increased in the solid dielectric. The breakdown in the water and the solid dielectric is governed by its own breakdown voltage and by the corresponding value of the average field intensity $E_k=U_k/h$. This type of concentrator may be effective, if E_k is greater than E_0 where E_0 is the field intensity in water in the uniform field.
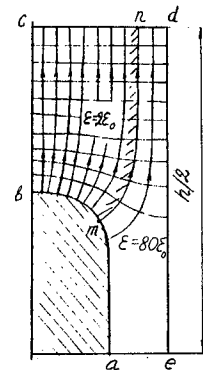

Fif.4. Voltage waveforms

a - Channel with even walls

b - Channel with profiled walls

Fig.5. Fragment of the system with $E_n=0$

a) electrode; b) solid dielectric ($\varepsilon \approx \varepsilon_0$);

c) liquid dielectric ($\varepsilon \approx \varepsilon_0$)

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